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Field Comparison of PM10
Inlets at Four Locations

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A Field Comparison of PM₁₀ Inlets at Four Locations

Charles E. Rodes, David M. Holland, Larry J. Purdue, Kenneth A. Rehme

Environmental Monitoring Systems Laboratory
U. S. Environmental Protection Agency
Research Triangle Park, North Carolina

A comprehensive field study was conducted comparing the performance of PM₁₀ inlets under a variety of field conditions. Inlets for low flow, medium flow, and high flow samplers were evaluated at four sampling locations providing a range of concentrations and particle sizes. Sampler precisions were determined at each location along with the regression parameter estimates comparing sampler types. The daily distributions of mass by aerodynamic diameter were measured using the Wide Range Aerosol Classifier and the composited data reported. The expected mass concentrations were calculated using the sampler effectiveness data and the size distributions and then compared to the measured values. This permitted examination of the utility of the proposed Federal Reference Method (FRM) approach for specifying PM₁₀ samplers.

The comparison results indicate that the precisions of the PM₁₀ samplers are well within the FRM requirements. The performance of the inlets as characterized by wind tunnel testing provided computed results which in most cases were within $\pm 10\%$ of the measured values. Exceptions included the Sierra/Andersen Model 321 hi-vol inlet, which appears to significantly overcollect as the result of dry particle bounce, and the GMW 9000 hi-vol inlet, which appears to significantly undercollect, perhaps as the result of the internal surfaces becoming dirty.

In 1971 the U.S. Environmental Protection Agency (EPA) promulgated standards¹ for total suspended particulate (TSP). Subsequently, analyses of health studies and other pertinent scientific criteria suggested that serious consideration be given to the regulation of that size fraction of particulate matter which can deposit deep in the human respiratory tract. In 1979 Miller *et al.*² recommended that particulate research focus on inhalable particulates, those airborne particles having an aerodynamic equivalent diameter $\leq 15 \mu\text{m}$.

As a result of these assessments and recommendations, EPA initiated a particulate sampler development program and established an Inhalable Particulate (IP) Network to collect

concentration data in support of anticipated revisions to the National Ambient Air Quality Standards (NAAQS) for particulate matter. Much of the research EPA funded was directed toward the development of new sampling hardware and a better understanding of the separation processes attendant in particulate sampling devices. Sampler inlet designs were based primarily on performance specifications (50% cutpoint tolerance, allowable error due to dry particle bounce and wind speed and wind direction sensitivity, etc.) and inlet performance was characterized, for the most part, in wind tunnels.

A reassessment of particulate size considerations³ in 1982 resulted in a reduction of the upper cutpoint of interest from $15 \mu\text{m}$ to $10 \mu\text{m}$. Accordingly, existing IP sampling inlets were modified or redesigned to provide collection of particles $\leq 10 \mu\text{m}$ in aerodynamic equivalent diameter (PM₁₀) and many IP Network sites began to collect PM₁₀ concentration data.

On March 20, 1984, EPA proposed revisions to the NAAQS for particulate matter.⁴ New primary standards were proposed for particulate matter mea-

sured as PM₁₀, and if promulgated, would regulate only those particles that can deposit in the tracheobronchial and alveolar regions of the lung. A new Federal Reference Method (FRM) to determine particulate matter as PM₁₀ in the atmosphere was also proposed. Unlike the TSP reference method which specifies the sampler by unique design specifications, the proposed PM₁₀ FRM specifies samplers primarily by performance specifications. Samplers would be accepted if they performed satisfactorily in both laboratory (wind tunnel) and ambient air tests.

The wind tunnel performance specifications in the FRM were designed to provide samplers with 1) a 50% cutpoint of $10 \pm 1 \mu\text{m}$ and 2) calculated agreement ($\pm 10\%$) between concentration measurements made by candidate PM₁₀ samplers and an "ideal" model which is based on the respiratory deposition data of Chan and Lippmann.⁵ If the performance specifications accurately describe acceptable PM₁₀ inlets, they should result in samplers that provide ambient concentration measurements that are in reasonable agreement with one another. Although a substantial amount of performance data from wind tunnel testing of PM₁₀ inlets has become available over the last few years, very little field data are available to verify the sampler performance suggested by the wind tunnel studies.

A multi-city field study was designed in early 1983 to evaluate the performance of available PM₁₀ sampling inlets under field conditions and analyze the results in light of existing wind tunnel test data and the proposed FRM requirements. The study was designed specifically to estimate precision, determine relative biases between inlet types, determine daily total mass distributions by particle size, and compare measured particulate concentrations to computed values based on the mass

The authors are with the Environmental Monitoring Systems Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC 27711. This technical paper was submitted for peer review December 14, 1984; the revised manuscript was received February 5, 1985.

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Table I. PM₁₀ inlets.

Inlet vendor	Inlet model	Sampler base	Flow rate m ³ /min	Reference*
General Metal Works (GMW-40CFM)	9000	GMW Accu-Vol	1.13	10
Sierra/Andersen (S/A-40CFM-321)	321	GMW Accu-Vol	1.13	11
Sierra/Andersen (S/A-40CFM-321A)	321A	GMW Accu-Vol	1.13	12
Sierra/Andersen (S/A-4CFM)	254	S/A Med-Flo	0.113	13
General Metal Works (GMW-4CFM)	9100	GMW 554M	0.113	14
Sierra/Andersen (S/A-DCT)	246b	Sierra 244E	0.0167	15
General Metal Works (GMW-DCT)	9200	Sierra 244E	0.0167	16
Flow Sensors (FS-DCT)	85-16	Sierra244E	0.0167	
EPA (EPA-DCT)		Sierra 244E	0.0167	17

* Inlet sampling effectiveness data.

distribution and available wind tunnel data.

Previous field studies of particulate samplers⁶⁻⁹ were devoted almost solely to comparison of measured concentrations. Although this is the simplest approach, it does not quantitatively address the impact of different mass distributions and critical inlet performance parameters. This study collected mass distribution data concurrently with the measured concentrations, permitting computation of expected concentrations for each set of performance parameters. This provided estimates of bias not previously available, but substantially increased the overall complexity of the field operations.

The magnitude of a carefully designed study to evaluate the commercially available PM₁₀ inlets limited the effort to four geographic locations. Nearly two months were required at each site to set up the sampler array, the mass distribution monitoring system, and the analytical support facilities, and then operate for a statistically acceptable number of sampling periods. The prototype nature of some of the hardware, combined with improvements in the sampler technology during the course of the study, resulted in several hardware changes, a repeat of the testing at one location, and a delay of the final completion of the study.

This paper summarizes the data gathered at all locations during the study, analyzes the results in terms of particle sampling anomalies and the proposed PM₁₀ sampler performance specifications, and provides conclusions and recommendations concerning both sampler hardware and sampler performance specifications.

Experimental

PM₁₀ Inlets

The PM₁₀ inlets represented state of the art technology in May 1983 and were chosen primarily for commercial availability (Table I). The specific inlets, identified by vendor, model, and design flow rate, are listed in Table I along with the flow control systems used. Common flow control systems were used for both

the high and low flow inlet types to focus on the performance of the inlets rather than the total sampling system. Also shown are the references for the inlet sampling effectiveness data used in later calculations. Note that an acronym has been assigned to each inlet (shown in parentheses). These acronyms are used in subsequent discussions.

The inlets tested represent the three sampling flow rate ranges currently available—high flow (1.13 m³/min), medium flow (0.113 m³/min) and low flow (0.0167 m³/min). The GMW-40CFM, S/A-40CFM-321, and S/A-40CFM-321A are high flow inlets designed for use on conventional high-volume samplers. The S/A-40CFM-321A is an improved version of the S/A-40CFM-321 and was not available at the start of the study. The high flow inlets were operated on identical General Metal Works Accu-Vol bases and quartz filters (8 × 10 in.) were used for sample collection. The S/A-4CFM and GMW-4CFM are new designs with essentially no prior field evaluation. They were operated with vendor-designed flow control systems and quartz filters (102 mm diameter). The quartz filters used with the high and medium flow samplers were from a special batch of filters purchased by EPA and had been evaluated for artifact formation by Appel *et al.*¹⁸ The S/A-DCT, GMW-DCT, FS-DCT, and EPA-DCT are designed for use on dichotomous samplers, which separate PM₁₀ into FINE (0–2.5 μm) and COARSE (2.5–10 μm) fractions. The FS-DCT is a new design and was discontinued commercially by the vendor midway through the study. The EPA-DCT is not commercially available, but is an EPA-fabricated duplicate of a prototype of the GMW-DCT. The EPA-DCT was deployed in the IP Network in 1982. Although the GMW prototype was initially considered to be identical to the commercially available GMW-DCT, this early version was subsequently discovered to be dimensionally different and to have a higher cutpoint. The dichotomous sampler inlets were operated with identical Sierra/Andersen 244E flow control modules and 37 mm Teflon filters (2 μm porosity) were used for sample collec-

tion. All of the above inlets, except the FS-DCT, had been fully evaluated for PM₁₀ sampling effectiveness by the inlet designers or manufacturers using wind tunnel testing.

Wide Range Aerosol Classifier

The daily average mass distribution of particles at each location was measured with a Wide Range Aerosol Classifier (WRAC). It is an updated version of the system designed by Lundgren and Paulus to collect quantitative size distribution data up to 100 μm.^{19,20}

This classifier is a large trailer-mounted system of impactor stages, each of which collects a portion of the total mass distribution (Figure 1). It consists of four high flow (1.6 m³/min) slit impactor stages with cutpoints of 47, 34, 18.5 and 9.4 μm, designated as WRAC1, WRAC2, WRAC3, and WRAC4, respectively. These stages operate in parallel with a "total" stage, designated as WRAC5, which is an open channel with no impactor. The impactor stages are designed to trap the particles greater than the cutpoint on weighable, oil-coated shim stages and collect the remaining particles on backup quartz filters (8 × 10 in.). Standard high volume blowers with mass flow controllers, flow recorders, and calibration orifices were used to control and monitor flow rates. The WRAC stage cutpoints and internal losses for both wet and dry particles were verified independently²¹ at the University of Florida and the University of Minnesota. The cutpoints obtained agreed within a few percent. Using oil coated stages, the collection efficiency for wet or dry particles is nearly 100% as long as stage overloading does not occur.

In order to define the distribution below 9.4 μm, a low volume (0.085 m³/min) Lundgren cascade impactor samples the stream between the impactation stage and the backup filter of WRAC4. The Lundgren sampler contains four slit impactors which operate in series using rotating, oil-coated drum substrates followed by a quartz backup filter (102 mm diameter). The Lundgren sampler cutpoints are 14.5, 4.6, 1.55, and 0.45 μm, based on the evaluation of Rao and Whitby.²²

Sampling Sites

The selection of sampling sites for comparing particulate sampling systems is very important because the performance of sampler inlets can be affected by the character of the ambient aerosol and the mass distribution of particles as a function of aerodynamic size. Larger ratios of COARSE/FINE would be expected to result in the largest biases between inlets. Four locations were selected to provide expected atmospheres

of 1) "low" concentration ($PM_{10} < 50 \mu g/m^3$); 2) "medium" concentration (PM_{10} of $50-80 \mu g/m^3$) with equivalent FINE ($0-2.5 \mu m$) and COARSE ($2.5-10 \mu m$) fractions; 3) "high" concentration ($PM_{10} > 80 \mu g/m^3$) with COARSE $\gg$ FINE; and 4) "high" concentration with equivalent COARSE and FINE fractions. Based on data from EPA's IP Network, the locations selected were in Durham, NC; East St. Louis, IL; Phoenix, AZ; and Rubidoux, CA. The Phoenix site was located several hundred meters downwind of a road construction project and at times was subject to very heavy fugitive dust conditions. This was the only site which would not have met the proposed⁴ PM_{10} siting criteria. Data were collected in July/August 1983 for Durham, September/October 1983 for East St. Louis, December 1983/January 1984 for Phoenix (designated Phoenix I), March/April 1984 for Rubidoux, and a return visit for additional testing in Phoenix in May 1984 (designated Phoenix II).

Each sampling site required a substantial open area because of the large array of PM_{10} samplers, the size of the trailer-mounted WRAC system, and the mobile filter equilibration and weighing

laboratory. In Durham the PM_{10} samplers were located on the roof of a single story building adjacent to the parked WRAC and mobile laboratory. The WRAC inlet was at approximately the same elevation as the PM_{10} sampler inlets. In the other three cities, scaffolding was erected on paved parking lots to raise the PM_{10} sampler inlets to 3 m. All PM_{10} sampler types were operated in duplicate with their inlets spaced 2 m apart in a rectangular array (22×32 m). The array size and configuration were retained at all locations. Because of their excellent reproducibility, TSP high-volume samplers were located on three corners of the array at each site to identify possible spatial biases. No significant differences in TSP across the array were observed at any of the sites. Wind speed data were collected to examine possible correlations with observed data for sampler inlets known to be sensitive to wind speed. Most of the inlets tested are not affected significantly by wind speed from 2 to 24 km/h. Since the range of mean wind speeds encountered for all the sites was only 1.8-14.3 km/h, the effects were negligible compared to other experimental errors.

Sampler Operation

All samplers, including the WRAC, were operated simultaneously for 24-hour periods using the operating procedures and quality control measures of the IP Network.²³ To provide "best-case" results, filter handling was minimized by use of cassette holders, immediate equilibration after sampling, and weighing on-site. This also eliminated the need for folding or shipping filters. Quartz filters and their cassette holders were examined for excessive fiber loss following each sampling period. Daily flow rate calibration checks and setpoint readjustments were performed on all samplers to minimize biases due to flow calibration errors. The same control limits employed for the PM_{10} sample filters were used for weighing the WRAC impactor substrates and backup filters.

The results of the internal and external quality control checks indicated that the weighing and flow calibration activities were well within the limits set for the IP Network. The reproducibility of flow calibrations for all samplers was determined to be slightly better than 3%. The temperature and relative humidity stability for filter equilibration in the mobile lab were $\pm 2^\circ C$ and $\pm 3\%$, respectively.

Particulate concentration data were calculated using an on-site minicomputer to minimize computational errors and simplify data validation. Flow rate corrections were applied when before and after flow calibrations differed by more than 3%. Any discrepancies in concentration between duplicate samplers greater than 10% resulted in a reweighing of all affected filters and checks of the computational steps.

Expected PM_{10} measurement precisions of 10% or better (for duplicate samplers) required a minimum of 12 sampling days to detect biases of 5% between any two samplers. The actual number of sampling days were 17 in Durham, 15 in East St. Louis, 16 in Phoenix I, and 9 in Rubidoux. The number of days was reduced in Rubidoux because of the better than expected measurement precision and the somewhat lower than expected PM_{10} concentrations.

The S/A-40CFM-321A inlet was added in Rubidoux (to correct an apparent dry-particle bounce problem in the S/A-40CFM-321). After the completion of sampling in Rubidoux, a return visit of 11 sampling days was made to Phoenix to obtain additional data comparing the S/A-40CFM-321A with the other PM_{10} inlets and to test improvements made in the WRAC operating procedures.

A single inlet designed by Wedding and Weigand²⁴ to collect the TP-6 fraction (particles nominally $< 6 \mu m$)

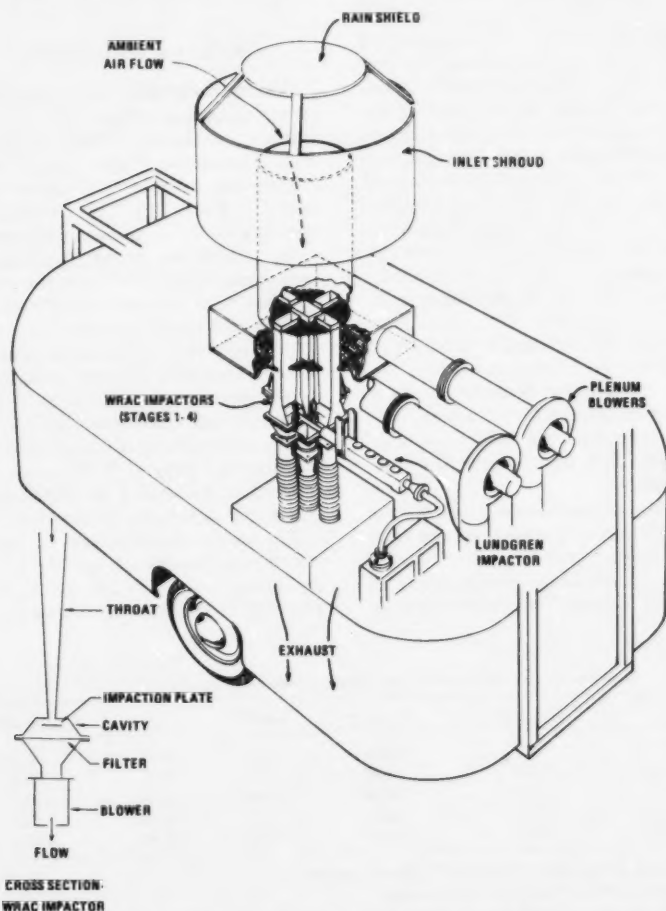


Figure 1. Diagram of Wide Range Aerosol Classifier (WRAC) system.

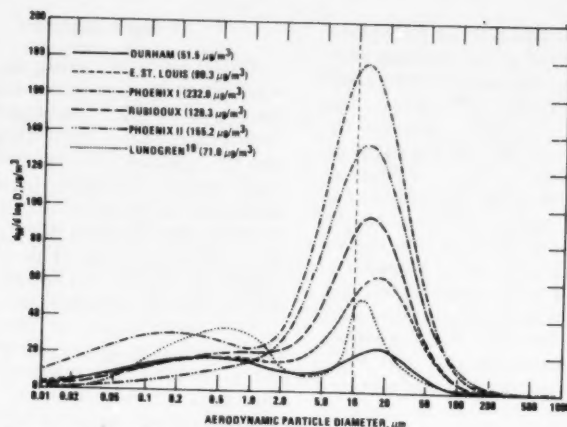


Figure 2. Composited size distributions.

was used in Rubidoux and during both visits to Phoenix to compare the PM_{10} and TP-6 fractions. All inlets except the TP-6 were disassembled and cleaned prior to operation in Rubidoux. None of the hardware was excessively dirty except the oil-impregnated surfaces of the GMW-40CFM and GMW-4CFM inlets. Internal dust coatings in the form of swirl pattern ridges, with thicknesses up to 3 mm, were present in these inlets on the cyclone outlet tube.

Results

This section summarizes the data in tabulated form to facilitate its interpretation. Although some discussion is contained within this section, more interpretive discussion concerning sampler performance is presented in subsequent sections.

Mass Distributions

Daily mass concentrations were initially computed for each stage of the WRAC system such that the fraction of mass for each stage could be manually plotted on a cumulative log-probability graph. Review of these plots indicated a strong lognormal relationship for the COARSE fraction except for an occasional positive bias for the point representing the WRAC4 fraction. Visual examination of the WRAC4 impaction stage during field sampling indicated that it was overloading at elevated ambient concentrations, resulting in particle bounce to the backup filter. This overloading phenomenon, previously noted by Lundgren and Rovell-Rixx,²⁵ can result in collection of significant amounts (typically 5–30 $\mu g/m^3$) of mass on stage 1 of the Lundgren sampler. Since stage 1 has a larger cutpoint than WRAC4, it should collect no more than a few $\mu g/m^3$. To correct for the particle bounce, the collection of Lundgren stage 1 was routinely deducted from that of the WRAC4 backup filter. In nearly

every case this improved the linearity of the COARSE mode as evident from the log-probability plots. In spite of the correction for particle bounce, overloading made the data for the WRAC system in Phoenix I more variable than data at the other sites. This resulted in distributions in which the computed PM_{10} concentrations are biased high.

To make the data points generated by the Lundgren sampler consistent with those from the WRAC, the sum of the Lundgren stages should be equal to the collection of the WRAC4 backup. Review of the data showed general agreement, but occasional differences resulted in significant discontinuities in the total cumulative distribution. These differences were primarily the result of difficulties in operating the Lundgren sampler, including the inaccuracy associated with large tare weights relative to the collected mass and the inadvertent loss of the oil coating during handling. Since accurate definition of the FINE mode is not critical for PM_{10} mass predictions, the Lundgren stage collections were utilized to define the shape of the distribution below 9.4 μm . The bounce-corrected WRAC4 concentrations were used to represent the fractional masses.

A six-parameter bimodal lognormal distribution model was fit by iteration to the daily cumulative mass concentrations to facilitate computation of predicted masses. The daily means of

the stage totals of WRAC1 through WRAC4 were used to represent the integrated total concentration (X_T) of the daily size distribution. Ordinarily the mass collected on WRAC5 would have been used to represent X_T ; however, the rim of the WRAC5 filter holder assembly was bent sometime during the study, resulting in questionable data.

The 24-hour average mass size distributions measured with the WRAC and composited by site are shown in Figure 2. The "typical" urban size distribution reported by Lundgren and Paulus¹⁹ and utilized in the proposed FRM is also shown. The mass median diameters, geometric standard deviations, and integrated total concentrations for the composited size distributions are given in Table II. The geometric standard deviations (σ_F) for the FINE mode are much larger than those in the literature, such as the value of $\sigma_F = 1.7$ reported by Whitby *et al.*²⁶ for the Los Angeles area. This discrepancy is believed to be the result of the small FINE fractions observed during the study, the relatively poor weighing accuracy obtained using the Lundgren sampler, and the limited number of data points defining the FINE mode.

Particulate Measurements

Summary statistics of the particulate measurements, composited by size fraction, are shown in Table III for each city. The mean PM_{10} concentration ranged from 37 $\mu g/m^3$ in Durham to 117 $\mu g/m^3$ in Phoenix I. These means corresponded to TSP levels of 48 and 255 $\mu g/m^3$. From the mean concentration values and COARSE/FINE ratios, it is apparent that the four locations met the desired site characteristics reasonably well. Completion of most of the road construction after Phoenix I resulted in much lower concentrations in Phoenix II and higher COARSE/FINE ratios. The combination of the large COARSE fraction and very high PM_{10} concentrations in Phoenix I provided an extreme test of sampler performance.

The mean concentrations for the duplicate samplers of each type for all days are shown in Table IV for each location. The FINE fractions collected by the

Table II. Composite parameters for size distributions by site.

Site	$D_F, \mu m^a$	$D_C, \mu m^a$	$\sigma_F^{b,c}$	σ_C^b	$X_T, \mu g/m^3^d$
Durham	0.37	17.44	5.72	2.09	51.5
E. St. Louis	0.53	17.00	7.85	2.18	90.3
Phoenix I	0.21	12.96	7.89	2.28	232.0
Rubidoux	0.94	13.94	8.01	2.13	126.3
Phoenix II	0.71	13.01	6.20	2.51	155.2

^a Mass median diameters by mode, F-fine, C-coarse.

^b Geometric standard deviations by mode.

^c Probably in error, see text.

^d Total mean concentration in size distribution.

Table III. Summary statistics for TSP, PM₁₀, COARSE and FINE observations (μm^3).

Variable	N	Mean	Standard deviation	Minimum value	Maximum value
Durham					
TSP	68	47.6	15.2	17.3	81.2
PM ₁₀	266	36.9	12.8	5.6	66.2
COARSE	132	11.1	4.4	2.9	23.8
FINE	132	28.0	10.8	8.8	48.9
Ratio (C/F)	132	0.5	0.3	0.1	1.5
E. St. Louis					
TSP	60	90.9	42.9	18.0	152.9
PM ₁₀	236	49.8	24.6	11.7	100.7
COARSE	120	23.8	11.2	2.5	41.6
FINE	120	27.6	15.1	11.2	58.8
Ratio (C/F)	120	0.9	0.4	0.2	2.5
Phoenix I					
TSP	63	254.5	90.9	98.5	451.8
PM ₁₀	216	117.2	41.2	42.4	269.4
COARSE	106	83.9	31.9	28.9	167.4
FINE	106	37.1	10.9	16.6	53.2
Ratio (C/F)	106	2.3	0.9	1.4	5.0
Rubidoux					
TSP	26	109.0	19.4	72.9	142.8
PM ₁₀	118	64.4	15.9	29.2	97.7
COARSE	52	36.9	7.8	18.1	53.4
FINE	52	27.9	10.8	12.1	48.1
Ratio (C/F)	52	1.5	0.5	0.7	2.7
Phoenix II					
TSP	33	141.5	40.2	81.2	243.7
PM ₁₀	131	72.1	18.5	41.5	118.6
COARSE	65	57.6	13.4	37.3	89.1
FINE	65	16.6	3.6	11.4	24.9
Ratio (C/F)	65	3.6	0.8	2.0	5.3

dichotomous samplers were in excellent agreement at all sites, demonstrating consistent sampler operation. The differences in the COARSE fraction means primarily reflect differences in inlet performance. Data from one of the GMW-DCT duplicate samplers were invalidated in Phoenix I due to a leaking flow regulator. The data from the other sampler, although included in the data analysis, are suspect because of similar erratic behavior of the flow regulator.

The PM₁₀ concentrations measured with the 4CFM samplers were generally lower than those measured with the other samplers. The filter holders of both sampler types were new designs and neither prevented damage to the quartz filters. The GMW-4CFM filter holders were especially poor. The vendor redesigned the holders after Durham and new handling procedures were developed during the East St. Louis sampling. Both 4CFM samplers were oper-

ated in Phoenix I using the redesigned holders and improved procedures with no evidence of significant substrate losses.

After Phoenix I the FS-DCT inlet was discontinued commercially by the vendor and was withdrawn from the study. The GMW-4CFM and S/A-4CFM inlets were withdrawn from the study after Phoenix I and Rubidoux, respectively, because of the prototype nature of the samplers, the need to reduce the complexity and cost of the study, and the decision to place the emphasis on the sampler types most widely used (high-volume and dichotomous). In addition, the GMW-4CFM data closely resembled that of the generically similar GMW-40CFM inlet. The S/A-40CFM-321A was incorporated into the study beginning in Rubidoux.

Precision

Preliminary analysis of the duplicate observations for each PM₁₀ sampler suggested that precision of measurement was proportional to the level of measurement. Therefore, an estimate of a coefficient of variation (CV), which characterizes the error variation of a given PM₁₀ sampler was used to express precision. Utilizing discussion by Mosteller²⁷ describing the distribution of the relative difference (difference of the paired values expressed as a percentage of the paired average), estimates of the CV were computed.

These estimates, shown in Table V, indicate that the precision of the majority of samplers and measurement fractions is within 10%. The operating and quality assurance procedures used in this study were designed to provide "best-case" precision to make comparisons between samplers as meaningful as

Table IV. Sampler summary statistics ($\bar{X}$, s) for the FINE, COARSE and PM₁₀ particulate levels ($\mu\text{g}/\text{m}^3$).

Sampler		Durham 17 sampling days		E. St. Louis 15 sampling days		Phoenix I 16 sampling days		Rubidoux 9 sampling days		Phoenix II 11 sampling days	
		$\bar{X}$	s	$\bar{X}$	s	$\bar{X}$	s	$\bar{X}$	s	$\bar{X}$	s
FINE	S/A-DCT	29.0	11.2	28.0	15.8	37.5	10.9	27.5	11.2	16.9	3.9
	FS-DCT	28.2	11.3	28.0	15.7	37.0	10.8	a	a	a	a
	GMW-DCT	27.4	10.8	27.6	15.1	35.8 ^b	10.9	27.6	11.4	16.2	3.6
	EPA-DCT	27.8	10.8	27.0	15.4	36.3	10.8	27.9	11.5	16.7	3.3
COARSE	S/A-DCT	11.2	4.1	23.7	11.3	82.9	31.6	36.3	7.9	55.5	13.3
	FS-DCT	11.1	4.3	23.7	10.9	77.6	29.0	a	a	a	a
	GMW-DCT	10.1	4.1	21.7	10.6	70.2 ^b	25.8	33.5	7.1	55.3	12.8
	EPA-DCT	11.7	4.3	25.7	12.5	92.8	34.4	40.3	7.7	61.8	14.1
PM ₁₀	S/A-DCT	40.1	12.4	51.7	25.8	120.4	38.5	63.8	15.2	72.4	15.7
	FS-DCT	39.3	12.5	51.7	24.9	114.7	36.2	a	a	a	a
	GMW-DCT	37.5	11.6	49.5	24.7	106.0 ^b	34.1	61.1	15.4	71.4	15.4
	EPA-DCT	39.5	12.2	52.7	26.0	129.2	41.9	67.9	16.1	78.5	16.2
	S/A-4CFM	34.2	12.8	46.8	24.1	113.1	37.6	64.8	16.4	a	a
	GMW-4CFM	31.9	14.3	43.0	21.6	99.3	32.0	a	a	a	a
	GMW-40CFM	35.1	12.4	44.0	23.9	97.3	29.6	58.1	16.3	51.5	10.5
	S/A-40CFM-321	38.1	12.7	56.7	27.8	144.2	53.7	71.2	16.9	88.8	18.0
	S/A-40CFM-321A	a	a	a	a	a	a	61.9	17.3	70.1	13.7

^a Sampler not operated.

^b Single sampler, questionable data, see text.

Table V. Sampler precision estimates (%) for each site.

	Durham	E. St. Louis	Phoenix I	Rubidoux	Phoenix II
FINE					
S/A-DCT	8.6	6.4	3.2	4.4	7.0
FS-DCT	3.4	4.9	8.2	a	a
GMW-DCT	2.8	8.5	b	3.2	4.0
EPA-DCT	6.6	11.4	3.6	4.4	6.6
COARSE					
S/A-DCT	13.2	8.4	2.6	5.3	3.0
FS-DCT	13.4	5.7	8.7	a	a
GMW-DCT	18.3	9.2	b	1.3	2.8
EPA-DCT	18.3	11.6	2.6	4.9	2.8
PM ₁₀					
S/A DCT	5.0	6.6	1.2	3.0	3.4
FS-DCT	4.5	4.2	8.5	a	a
GMW-DCT	4.9	6.2	b	1.6	2.3
EPA-DCT	6.6	9.2	2.6	3.8	2.2
S/A-4CFM	20.7	8.2	2.1	3.4	a
GMW-4CFM	22.9	9.3	4.5	a	a
GMW-40CFM	3.1	4.4	1.5	1.5	2.5
S/A-40CFM-321	3.0	4.9	2.3	2.3	3.4
S/A-40CFM-321A	a	a	a	2.3	2.0

^a Sample not operated.

^b Single sampler, see text.

possible. Because of the size and complexity of the study, a learning period was expected in Durham. The data indicate that only after East St. Louis did the sampler precisions stabilize. The poor precision for the 4CFM samplers in Durham can be attributed to the filter holder design problems cited earlier. Overall, the precision estimates for the PM₁₀ samplers at the last three sites were considered extraordinarily low for all samplers and are probably at least a factor of two better than those reported²⁸ for routine IP Network measurements.

Sampler Comparisons

The relationships between PM₁₀ samplers are of major interest in evaluating the proposed FRM criteria. If ambient measurements are not in reasonable agreement ($\pm 10\%$), the FRM approach may not adequately define the sampling process. The slope (β) and intercept (α) of a linear regression rela-

tionship provide estimates of the proportional and constant differences, respectively, between any two PM₁₀ samplers. To account for the measurement error associated with each sampler of interest, an error in both variables regression analysis²⁹ was utilized to determine estimates of the nature of the differences between any two samplers.

Where regressions for specific paired samplers can be shown to be statistically identical across sites, the data can be combined in order to make inferences about the paired samplers with increased confidence. A general procedure³⁰ was used to test the equivalence of the linear relationships across sites at a 5% significance level. Although this pooling test is based on simple linear regression, it was used to provide a criterion for pooling data from which the parameters of a regression line could be estimated while accounting for errors in both variables.

Regression parameters were estimated for all possible paired sampler

Table VI. Regression parameters for pooled PM₁₀ comparisons.^a

Sampler comparison	n	r	α	β
FS-DCT vs. S/A-DCT	48	0.99	2.37 ^b	0.94 ^b
EPA-DCT vs. S/A-DCT	68	0.99	-2.95 ^b	1.09 ^b
GMW-4CFM vs. S/A-DCT	45	0.98	-2.59	0.87 ^b
FS-DCT vs. GMW-DCT	47	0.99	-1.26	1.08 ^b
GMW-4CFM vs. GMW-DCT	44	0.98	-5.89 ^b	1.00
GMW-40CFM vs. FS-DCT	46	0.99	-1.42	0.90 ^b
GMW-4CFM vs. FS-DCT	45	0.98	-6.03 ^b	0.95 ^b
S/A-4CFM vs. FS-DCT	46	0.99	-8.45 ^b	1.09 ^b
GMW-4CFM vs. EPA-DCT	45	0.98	-0.15	0.80 ^b
S/A-4CFM vs. EPA-DCT	55	0.99	-1.72	0.93 ^b
GMW-4CFM vs. S/A-40CFM-321	45	0.97	6.80 ^b	0.64 ^b
GMW-4CFM vs. GMW-40CFM	45	0.98	-4.04 ^b	1.05
S/A-40CFM-321A vs. S/A-DCT	18	0.92	1.36	0.96
S/A-40CFM-321A vs. EPA-DCT	18	0.96	1.69	0.89 ^b

^a Parameter α = intercept; β = slope.

^b Reject hypothesis $\alpha = 0$ or $\beta = 1$ at a 5% significance level.

combinations for the PM₁₀ and dichotomous FINE fraction measurements. Separate comparisons of the dichotomous COARSE fractions are not presented because they are reflected in the PM₁₀ comparisons. Data for the dichotomous FINE fraction comparisons indicated that all measurements were statistically identical at a 5% significance level. The pooling test for the PM₁₀ comparisons indicated that data could not be combined for the majority of the paired sampler types. The regression estimates for comparisons where data could be pooled are shown in Table VI and the regression estimates for selected comparisons where data could not be pooled are shown in Table VII.

All of the slopes shown in Table VI were within $\pm 10\%$ except for three comparisons involving the GMW-4CFM sampler and the comparison of the S/A-40CFM-321A with the EPA-DCT sampler. Of the 48 selected comparisons shown in Table VII, 18 had statistically significant slopes that differed from unity by more than $\pm 10\%$. Of these, eight occurred in Phoenix I where the particulate concentrations were extremely high and the mean COARSE/FINE ratio was 2.3. Eight others occurred in Phoenix II where the particulate concentrations were moderate and the mean COARSE/FINE ratio was 3.6, and two occurred in East St. Louis.

Accuracy

The accuracy of particulate measurements is very difficult to address without a reference sampler or calibration device. The proposed FRM for PM₁₀ specifies a calculated agreement ($\pm 10\%$) in expected mass between candidate samplers and an "ideal" sampler. This specification is based on determining sampling effectiveness in wind tunnels and an assumed "typical" size distribution. The proposed FRM assumes that samplers meeting this requirement would provide a reasonably accurate measure of PM₁₀ concentrations in ambient air. Estimates of "accuracy" in this study are based on comparison of observed PM₁₀ concentrations with those computed from the daily mass distribution data and the sampling effectiveness data for each inlet. These estimates are more measures of the "predictability" of the performance of inlets than measures of accuracy.

Utilizing the method described by Cooper and Davis³¹ and refined by Wedding and Carney,³² the expected mass concentrations for each sampler were computed by integrating the sampling effectiveness data for each inlet (Table I) with the daily mass distributions. The ratios (β) of the mean observed concentrations to the mean computed concentrations for each

Table VII. Regression parameters for unpooled PM₁₀ comparisons.^a

Sampler comparison	n	r	α	β
1. GMW-DCT vs. S/A-DCT				
Durham	17	0.97	-0.12	0.94
E. St. Louis	15	0.99	-0.03	0.96
Phoenix I	15	0.99	2.87	0.86 ^b
Rubidoux	9	0.97	-3.35	1.01
Phoenix II	11	0.97	0.03	0.99
2. S/A 40CFM-321 vs. S/A-DCT				
Durham	17	0.99	-3.52	1.04
E. St. Louis	15	0.99	0.97	1.08 ^b
Phoenix I	16	0.99	-17.86 ^b	1.39 ^b
Rubidoux	9	0.98	-0.12	1.12
Phoenix II	11	0.98	5.26	1.15 ^b
3. GMW-40CFM vs. S/A-DCT				
Durham	17	0.99	-5.22 ^b	0.99
E. St. Louis	15	0.99	-4.04 ^b	0.93 ^b
Phoenix I	14	0.99	7.18	0.77 ^b
Rubidoux	9	0.90	-17.11	1.18
Phoenix II	11	0.96	2.47	0.68 ^b
4. S/A-4CFM vs. S/A-DCT				
Durham	17	0.95	-6.38 ^b	1.01
E. St. Louis	15	0.99	-1.43	0.93 ^b
Phoenix I	14	0.99	-0.57	0.98
Rubidoux	9	0.95	-2.07	1.05
Phoenix II				
5. EPA-DCT vs. GMW-DCT				
Durham	17	0.98	0.32	1.05
E. St. Louis	15	0.99	0.98	1.05
Phoenix I	15	0.99	-5.83	1.28 ^b
Rubidoux	9	0.99	3.97	1.05
Phoenix II	11	0.98	2.88	1.06
6. CMW-40CFM vs. GMW-DCT				
Durham	17	0.97	-5.61	1.07
E. St. Louis	15	0.99	-3.89 ^b	0.97
Phoenix I	13	0.99	6.33	0.88 ^b
Rubidoux	9	0.97	-7.61	1.07
Phoenix II	11	0.99	2.75	0.68 ^b
7. GMW-40CFM vs. EPA-DCT				
Durham	17	0.99	-5.68	1.02
E. St. Louis	15	0.98	-4.96	0.93
Phoenix I	14	0.99	7.93	0.72 ^b
Rubidoux	9	0.95	-13.66	1.06
Phoenix II	11	0.98	0.92	0.65 ^b
8. GMW-40CFM vs. S/A-40CFM-321				
Durham	17	0.99	-1.94	0.96
E. St. Louis	15	0.99	-4.91 ^b	0.86 ^b
Phoenix I	14	0.95	18.03 ^b	0.55 ^b
Rubidoux	9	0.95	-13.03	0.99
Phoenix II	11	0.91	-1.26	0.59 ^b
9. S/A-4CFM vs. GMW-4CFM				
Durham	17	0.88	4.92	0.92
E. St. Louis	14	0.98	0.76	1.11 ^b
Phoenix I	14	0.99	-4.56	1.19 ^b
Rubidoux				
Phoenix II				
10. S/A-40CFM-321A vs. GMW-DCT				
Durham				
E. St. Louis				
Phoenix I				
Rubidoux	7	0.97	-5.44	1.14
Phoenix II	11	0.99	7.14 ^b	0.88 ^b
11. S/A-40CFM-321A vs. S/A-40CFM-321				
Durham				
E. St. Louis				
Phoenix I				
Rubidoux	7	0.96	-8.07	1.01
Phoenix II	11	0.93	5.28	0.73 ^b
12. S/A-40CFM-321A vs. GMW-40CFM				
Durham				
E. St. Louis				
Phoenix I				
Rubidoux	7	0.97	4.77	1.02
Phoenix II	11	0.99	3.33	1.30 ^b

^a Parameter α = intercept; β = slope.

^b Reject hypothesis $\alpha = 0$ or $\beta = 1$ at a 5% significance level.

sampler are shown in Table VIII. Sampling effectiveness data for both clean¹¹ and dirty³³ GMW-40CFM inlets were available and ratios for both conditions are tabulated. Ratios are also presented for the dichotomous FINE fractions (based on the mean values for all the dichotomous samplers in each city and the effectiveness data of Loo *et al.*³⁴) and for the TP-6²⁴ and conventional high-volume³⁵ samplers. Calculations were not made for the FS-DCT because complete effectiveness data were not available. The ratios in Table VIII indicate a generally acceptable level of agreement (within $\pm 10\%$) between most of the observed and expected values. Of the seven ratios tabulated for the 4CFM samplers, six were outside this range. Of the remaining 31 ratios for the PM₁₀ samplers, only five were outside this range.

Discussion

An assessment of the differences between PM₁₀ samplers (Tables VI and VII) and the ratios of observed to expected concentrations for each sampler (Table IX) should provide an indication of the adequacy of the performance-based approach of the FRM. If the mass concentration measurements of all the PM₁₀ samplers agree with one another within 10% under field conditions it is reasonable to assume that the FRM approach adequately predicts sampler performances. As discussed earlier, several of the comparisons in Tables VI and VII had statistically significant slopes that differed from unity by more than 10%. These results do not necessarily indicate that the FRM approach is inadequate, because of the possibility of inaccurate or incomplete performance information for the samplers and problems such as those experienced with the filter holders and operational procedures for the 4CFM samplers. Statistically significant differences between samplers greater than 10% will be examined relative to the performance characteristics reported for the samplers and new performance information obtained during the course of the study. An assessment of the ratios of observed to expected concentrations for each sampler provides an indication of how well wind tunnel test results predict sampler performance under ambient sampling conditions.

Dichotomous Samplers

The pooling test for the dichotomous sampler FINE fraction comparisons indicated that the data could be combined across sites to estimate the regression parameters in every case. Estimates of the intercepts and slopes indicated a very high degree of agreement between the paired samplers. The hy-

Table VIII. Estimates of proportional agreement between observed and expected values.

Sampler	Durham		E. St. Louis		Phoenix I		Rubidoux		Phoenix II	
	n	β	n	β	n	β	n	β	n	β
OS/A-DCT	8	1.04	10	0.97	6	0.92	8	0.94 ^b	10	1.04
GMW-DCT	8	0.98	10	0.94	5	0.76 ^b	8	0.91 ^b	10	1.02
EPA-DCT	8	1.03	10	0.96	6	0.95	8	0.99	10	1.10 ^b
S/A-4CFM	8	0.89	10	0.86 ^b	6	0.88 ^b	8	0.98		a
GMW-4CFM	8	0.85	9	0.78 ^b	6	0.80 ^b		a		a
GMW-40CFM	8	0.95	10	0.86 ^b	6	0.82 ^b	8	0.93 ^b	10	0.80 ^b
GMW-40CFM(d)	8	1.01	10	0.98	6	0.99	8	1.10 ^b	10	1.03
S/A-40CFM-321	8	1.01	10	1.06 ^b	6	1.09 ^b	8	1.03	10	1.22 ^b
S/A-40CFM-321A		a		a		a	6	1.03	10	1.08 ^b
DCT Fine	8	0.85 ^b	10	0.81 ^b	6	0.61 ^b	8	0.84 ^b	10	0.85 ^b
TP6		a		a	4	0.76 ^b	8	0.87 ^b		a
TSP HiVol	8	1.06 ^b	10	1.13 ^b	6	1.15 ^b	8	1.01	10	1.05 ^b

^a Sampler not operated.

^b Reject hypothesis $\beta = 1$ at a 5% significance level.

pothesis $\alpha = 0$ could not be rejected for any of the comparisons. Although the hypothesis $\beta = 1$ was rejected for two of the comparisons, all of the proportional differences were within 4%. This excellent agreement is better than expected considering the experimental errors normally associated with flow measurement and filter weighing. The ratios of the observed to expected concentrations for the FINE fraction (Table VIII) are consistently low at all sites. This reflects an apparent inaccurate distribution of mass, resulting from the difficulties associated with determining the stage weight gains for the Lundgren sampler, and perhaps some uncorrected particle bounce from the WRAC stages.

The PM₁₀ measurements obtained by all the dichotomous samplers generally agreed throughout the study. The proportional differences between paired dichotomous samplers were within 10% except for the GMW-DCT comparisons with the S/A-DCT and EPA-DCT in Phoenix I, where the erratic behavior of the GMW-DCT's flow system confounded the data. Only the data for these two comparisons could not be pooled across sites.

The EPA-DCT sampler was generally biased high relative to the other samplers except the S/A-40CFM-321. As noted earlier the EPA-DCT inlet has a different geometry and cutpoint than the currently available GMW-DCT version. This difference in geometry resulted from design changes to improve the original GMW prototype from which the EPA-DCT was modeled. The EPA-DCT inlet has been reported by Kashdan *et al.*¹⁷ to have a D_{50} of approximately 11 μm based on round-robin tests in three wind tunnels. This high cutpoint accounts reasonably well for the increased collection observed with this inlet.

The ratios for the dichotomous samplers in Table VIII show that the observed and expected concentrations agreed within 10% at all sites, except for the GMW-DCT in Phoenix I. This

demonstrates that the FRM approach adequately predicts the performance of these samplers under a variety of field sampling conditions.

40CFM Samplers

The GMW-40CFM sampler tended to collect less particulate matter than the other samplers throughout the study. Of particular interest is the trend of the site to site comparisons of this sampler with the dichotomous samplers (Table VII, #3, #6, #7). The regression slopes were near unity in Durham but decreased as the study progressed to East St. Louis and Phoenix I. After Phoenix I when the inlets were cleaned, the regression slopes increased in Rubidoux only to drop drastically again in Phoenix II.

After the study was completed the exposed GMW-40CFM inlet was tested in EPA's wind tunnel facility at Research Triangle Park. Test results³³ indicated that the D_{50} for this "dirty" inlet was 6.5 μm , compared to a value of 10.0 μm reported for the clean inlet. This change in cutpoint, which may result from accumulation of particulate matter within the inlet, could account for the

generally good agreement with the dichotomous samplers when the inlet was clean and the significant divergence after eight to ten days of sampling. The computed daily ratios of observed to expected concentrations for the GMW-40CFM and two dichotomous inlets in Rubidoux and Phoenix II are shown graphically in Figure 3. The ratios track each other in Rubidoux, but diverge significantly in Phoenix II. When the expected concentrations for the GMW-40CFM in Phoenix II are computed based on the "dirty" inlet effectiveness data, substantially better agreement with the other samplers is evident (Table VIII).

The S/A-40CFM-321 sampler tended to collect significantly more particulate matter than the other samplers throughout the study. This can be seen very clearly in the comparison with the S/A-DCT (Table VII, #2) and in the ratios of observed to expected concentrations (Table VIII). Note that the degree of overcollection increases as the site to site COARSE to FINE ratio increases (Durham < East St. Louis < Rubidoux < Phoenix II < Phoenix I). Wind tunnel test data provided by the vendor at an early stage of the study demonstrated that the inlet had excessive dry particle bounce. Reentrainment of collected larger particles within the inlet may also be a problem. The inlet was subsequently redesigned¹² by addition of a second impaction stage and the improved version (S/A-40CFM-321A) made commercially available by the vendor. The new inlet was added to the study at the start of sampling in Rubidoux. Although the S/A-40CFM-321 inlet was discontinued by the vendor at that time, it was retained in the study because it is still being used by many state and local air monitoring agencies. PM₁₀ concentrations measured with the S/A-40CFM-321A sampler were substantially lower than those obtained by the S/A-40CFM-321 and were in rea-

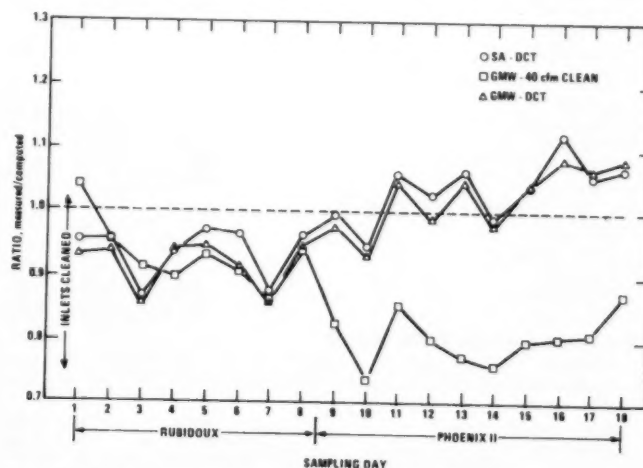


Figure 3. Ratio of measured to computed concentrations after cleaning.

sonably good agreement with the dichotomous sampler measurements.

4CFM Samplers

Results for both the 4CFM samplers (S/A-4CFM and GMW-4CFM) were adversely affected by the substrate loss problems cited earlier, particularly at the Durham and East St. Louis sites. These problems make assessment of the sampler comparison data difficult because of their potential effect on both the regression slopes and intercepts. Nevertheless, some general observations concerning the sampler comparison data can be made. The S/A-4CFM sampler appears to be in reasonable agreement with the dichotomous samplers. The GMW-4CFM sampler was generally biased low relative to the dichotomous samplers and agreed quite well with the physically similar GMW-40CFM sampler (Table VI). The ratios of observed to expected concentrations (Table VIII) for these two samplers were almost identical in Phoenix I and indicate that the GMW-4CFM inlet might be subject to a similar shift in cutpoint cited earlier for the GMW-40CFM inlet.

TP-6 Sampler

The ratios of observed to expected concentrations for the TP-6 sampler (Table VIII) also indicate an undercollection phenomenon similar to the GMW-40CFM and GMW-4CFM inlets. The TP-6 inlet appears to be affected to a greater degree than the two GMW PM₁₀ inlets, perhaps because this inlet must trap particles in the size range of 6–10 μm as well as particles greater than 10 μm .

Conclusions

This field evaluation of PM₁₀ samplers has provided a large data base representing a variety of inlet types and sampling situations. The complexity of the effort required nearly 12 months to complete the sampling and data analysis. During this time the sampling technology changed as did the commercial availability of some of the hardware.

The performance of the dichotomous samplers for both the FINE fraction and PM₁₀ measurements was excellent throughout the study. The PM₁₀ concentrations measured with the EPA-DCT are biased high relative to the other dichotomous samplers, but the biases are consistent with the 11 μm cutpoint reported for the inlet. The results of this study show that even though the dichotomous samplers are complex and difficult to operate, the experience gained and the sampler improvements made during the past five years have

resulted in repeatable and predictable samplers.

The undercollection observed for the GMW-40CFM sampler (and for the similar GMW-4CFM and TP-6 samplers) has been attributed, at least in part, to a shift in the cutpoint after the inlet became dirty. Expected mass concentrations calculated from wind tunnel effectiveness data for a dirty GMW-40CFM inlet are consistent with observed concentrations. Testing to verify this phenomenon is currently in progress.

The substantially higher than expected collections observed for the S/A-40CFM-321 sampler are attributable to excessive dry particle bounce. This effect has been verified by wind tunnel testing. The S/A-40CFM-321A sampler appears to be a significant improvement. However, recent work reported by Wedding *et al.*³⁶ suggests that the S/A-40CFM-321A may overcollect as a result of anisokinetic sampling at elevated wind speeds. The data from this study do not show an overcollection for this inlet, possibly because elevated wind speeds (≥ 40 km/h) were not encountered at any location more than 5% of the time. Since only limited field test data were obtained during this study, additional evaluation of this inlet is warranted.

Both 4CFM samplers gave results comparable to their high-volume and dichotomous sampler counterparts. Neither sampler, however, had been used extensively in the field, and the substrate loss problems which arose in Durham required immediate changes in the hardware and operating procedures. Nevertheless, this study has shown that the 4CFM approach to PM₁₀ sampling is viable, but some additional field experience to eliminate sampler problems may be needed. Further development of these 4CFM samplers should be pursued because of the advantages offered, especially because they can use either quartz or Teflon filters.

In general, the performance of the WRAC system during the study was acceptable except during the sampling in Phoenix I, which was marginal. The agreement between the computed and measured values for the PM₁₀ samplers tends to confirm an expected variability in the WRAC measurements of approximately $\pm 10\%$. The problem of stage overloading at elevated concentrations should be rectified to eliminate the need for between-stage corrections. A more operationally suitable impactor to define the FINE fraction would also be highly desirable. Another concern is the potential for inaccurate transport of the largest particles through the WRAC inlet to the first stage. Lundgren *et al.*²⁰ reported that the design criteria for a 10 km/h wind speed was less than a 20% error for 100 μm particles. Their test

results indicated that this criterion was met. The data from this study indicate a greater variability for collection on this stage, but an apparent minimal (if any) impact on the total mass collection.

The proposed FRM for PM₁₀ relies heavily on the validity of wind tunnel data and the representativeness of the specified size distribution to predict sampler performance under field conditions. The results of this study indicate that samplers meeting the cutpoint and dry particle bounce requirements of the FRM will agree reasonably well ($\pm 10\%$) under a variety of field conditions. The effect of deviations in the cutpoint from the 10 μm specification on ambient PM₁₀ measurements is illustrated by the results for the EPA-DCT and the GMW-40CFM (dirty) inlets.

The limit proposed in the FRM for allowable dry particle bounce (5% for 20 μm particles) was selected with little available information on the effect of particle bounce on collected mass. The effect of ambient mass measurements is dependent on the proportion of particles in the ambient distribution which behave as "dry" particles. This proportion is site dependent as is reflected in the data for the S/A-40CFM-321 which exhibited the greatest overcollection in Phoenix. The phenomenon is exaggerated by the extremely large proportion of COARSE mode particles in Phoenix and by their crustal nature, which tends to make the particles more prone to bounce. The 5% bounce specification appears to be reasonable in terms of biasing the mass collection, being within the detection limits of the bounce test, and the capabilities of existing technology inlets.

The size distribution selected for the expected mass calculations in the FRM was based on the available data and was assumed to be "typical." This study has provided a range of size distributions, and their impact on expected mass computations can be assessed. The size distributions composited for each site in this study and the FRM approach were used to compare concentrations computed for the inlet with those computed for the ideal sampler. These ratios (candidate inlet/ideal) are shown in Table IX for each site and for the "typical" distribution specified in the proposed FRM. All of the composited distributions except Durham are more stringent than the one proposed. Only the S/A-40CFM-321 fails to meet the $\pm 10\%$ requirement (in Phoenix II). This failure is the result of a high cutpoint and significant "tail" on the effectiveness curve. The selection of a more representative and stringent distribution for the FRM is currently under consideration.

The need to require wind tunnel testing of inlets under both "clean" and "dirty" conditions also warrants con-

Table IX. Ratios of computed concentration for inlet to computed concentration for ideal sampler.

	S/A-DCT	GMW-DCT	EPA-DCT	S/A-4CFM	GMW-4CFM	GMW-40CFM	S/A-40CFM-321	S/A-40CFM-321A
FRM	1.018	1.017	1.039	1.023	1.001	0.994	1.038	0.992
Durham	1.024	1.025	1.032	1.024	1.015	1.002	1.038	1.005
E. St. Louis	1.036	1.039	1.057	1.038	1.017	0.994	1.068	0.997
Phoenix I	1.038	1.048	1.065	1.036	1.018	0.985	1.075	0.989
Rubidoux	1.043	1.051	1.068	1.041	1.024	0.993	1.078	0.997
Phoenix II	1.058	1.073	1.091	1.054	1.034	0.988	1.106	0.995

sideration. The interlaboratory variability of wind tunnel measurements should be investigated through round-robin testing. Further work is also needed to verify that wind tunnel measurements are adequately representative of "real world" sampling situations.

The overall objective of evaluating available PM₁₀ hardware in light of the proposed FRM has been accomplished in this study. A variety of sampling and operational problems were identified and corrective actions initiated. The effects of nonideal inlet behavior such as shifts in cutpoint and dry particle bounce are now better understood. The "best-case" reproducibilities of all of the samplers have been shown to be much better than previously demonstrated due to the improvements in hardware and operational skills. The utility of the Wide Range Aerosol Classifier and the computational approach of Wedding and Carney³² have also been established.

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